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**INDIAN PROGRAMME RELATED TO INNOVATIVE
NUCLEAR REACTOR TECHNOLOGY**

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Abstract

The R&D road map for thorium utilisation and closed fuel cycle based third stage of the Indian nuclear programme is based on current Indian strengths and national priorities, as well as internationally stipulated desirable features of next generation nuclear reactor and fuel cycle technologies. The three major deliverables of this technology road map are:

1. Advanced Heavy Water Reactor
2. Compact High Temperature Reactor
3. Accelerator Driven System

For each of these deliverables, several enabling technologies are required to be developed. Most of these enabling technologies are candidates for international co-operative R&D. These newer technologies are expected to produce important spin-off benefits in non-nuclear fields as well.

1. Background

Indian nuclear programme and its priorities have been primarily determined by a need for self-reliance to attain long-term security of its energy supply. For a large country like India, with huge future energy requirements, depending largely upon import of energy resources is neither economically sustainable nor strategically sound. Domestic energy resources must therefore continue to be a major contributor to Indian energy supply. Currently known Indian reserves of hydrocarbon based fuel as well as uranium can not sustain even a modest per capita electricity consumption rate of about three-fourth of current world average, for more than a few decades [1]. The priorities for the Indian nuclear power programme were, accordingly, set more than forty years ago: the Indian programme must be based on closed fuel cycle and utilisation of thorium, of which India has nearly one-third of the world resources. The well known three stage Indian nuclear power programme [2] was accordingly drafted.

Today, with twelve Pressurised Heavy Water Reactors (PHWR) currently operating with excellent performance, and several others under construction and planning, the major thrust for future R&D in PHWR technologies has expectedly narrowed down mainly to life management of some critical components. Indigenous development and assimilation of Fast Breeder Reactor (FBR) technology has already culminated in the design of Prototype Fast Breeder Reactor (PFBR), and its construction is imminent. Several modest but important Indian initiatives for thorium utilisation, including successful operation of KAMINI, the only thorium fuelled reactor operating the world, and several laboratory or prototype level R&D programmes, have laid the foundation for a future development of thorium fuel cycle technologies for commercial level deployment.

With this background, during the last few years a detailed assessment of future Indian R&D priorities has been done. This has led to preparing an R&D road map for thorium utilisation and closed fuel cycle based third stage of the Indian nuclear programme [3].

2. Drivers for the Technology Road Map for Thorium Utilisation

The road map has three major drivers:

1. Current Indian strengths of large, trained scientific and engineering human resources, R&D infrastructure, a vision driven governmental support for long range R&D programmes, accumulated experience in design, construction, operation and maintenance of nuclear power plants, and a well-developed industrial base.
2. National priorities and needs for not only grid-based electricity generation but also for other manifestations of energy demand such as non-electricity applications and non-grid based electricity.
3. Evolving international trends in spelling out the requirements for next generation nuclear power systems that are capable of safely and economically producing nuclear power at a much larger scale of deployment, including in regions that are, currently, not advanced in the nuclear field.

3. Major Deliverables

The technology road map for the third phase of Indian nuclear programme envisages the following three deliverables:

4. Advanced Heavy Water Reactor
5. Compact High Temperature Reactor
6. Accelerator Driven System

A brief description of each one of the above three deliverables is provided in the following paragraphs:

3.1 Advanced Heavy Water Reactor

The Indian Advanced Heavy Water Reactor (AHWR) is a vertical pressure tube type boiling light water cooled and heavy water moderated reactor with a nominal power of 300 MWe [4]. The reactor is fuelled with U^{233} -Th mixed oxide (MOX) together with Pu-Th MOX, with the former producing a major fraction of power. AHWR is nearly self-sustaining in U^{233} .

Heat removal from core is by natural circulation of coolant. No pump is provided in the primary circuit. As shown in figure 1, water-steam mixture from core rises through the tail pipes to enter the steam drum. In steam drum, separated water at saturated temperature mixes with feed water and flows down the downcomers to the inlet header. From inlet header, water enters core through inlet feeder pipes. Water receives heat from fuel bundles in the core and boiling starts.

- Passive core heat removal by natural circulation of liquid heavy metal coolant
- Passive power regulation and shutdown mechanism.
- Passive rejection of entire heat to the atmosphere under accidental condition
- Compact design to minimise weight of the reactor

Based on these guidelines a conceptual design of CHTR has been worked out [5]. In the current stage of design, which is illustrated in figure 2, the reactor core consists of

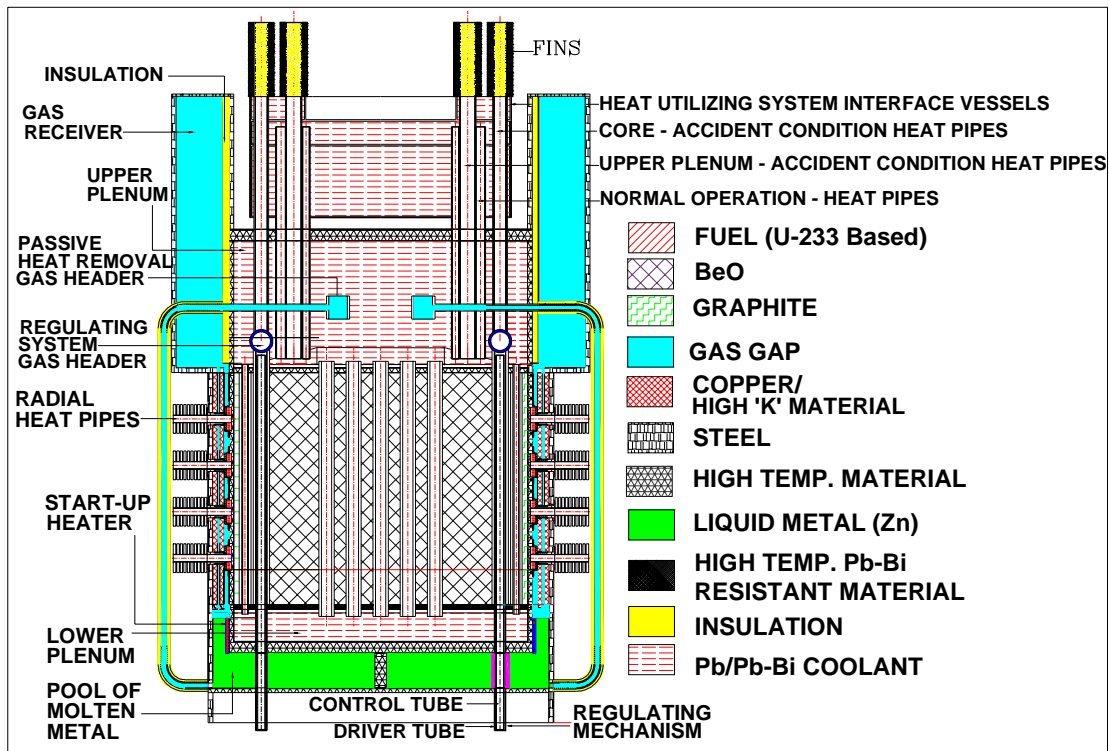


Fig. 2 Schematic of Compact High Temperature Reactor

nineteen prismatic beryllium oxide (BeO) moderator blocks (distributed in 1-6-12 arrangement). These blocks contain centrally located carbon fuel tubes. Each fuel tube carries within it the fuel inside 12 equi-spaced longitudinal bores. The fuel is in the form of pellets made by TRISO coated fuel particles. The central bore of the fuel tube serves as coolant channel. Eighteen blocks of beryllium oxide reflector then surround the moderator blocks. The beryllium oxide reflector blocks are surrounded by graphite blocks as additional reflector.

To remove heat from the reactor core, a lead-based liquid metal coolant flows by natural circulation between the top and bottom plenum, upward through the fuel tubes and returning through downcomer tubes. From the upper plenum of the reactor, heat pipes transfer heat to heat transfer interfaces of heat utilising systems. These heat utilising system interfaces provide the required environment, heat transfer area and interface hardware for energy conversion systems. The reactor has been provided with passive reactor power regulation system. The system uses core outlet coolant temperature as a driver to passively cause an extent of absorber insertion.

CHTR has been provided with four independent systems to reject entire core heat to the atmosphere by passive means during postulated accident conditions at a neutronicly limited peak power level. These heat removal systems, which are individually capable of removing 200 kW power each, may operate together or independently to prevent the temperature of the core and coolant from increasing beyond a set point. Of these four systems, three systems are heat pipe based systems.

Table-1 provides the major design parameters of CHTR

Table-1: Current Design Parameters of CHTR

Reactor power	100 kW _{th}
Core configuration	Vertical, Natural circulation type
Coolant	Molten Lead/ Lead-Bismuth eutectic
Number of fuel tubes	19 having 75 mm OD and 35 mm ID
Fuel	U ²³³ in Carbide form.(UC ₂). TRISO fuel particles, embedded in 12 nos. of cylindrical bores in carbon tubes
Moderator	BeO
Reflector	Combination of BeO and Graphite
Fuel heated length	0.7 m
Total core flow rate	1.13 kg/s
Coolant inlet temperature	400°C
Coolant outlet temperature	1000°C
Loop height	1.5 m
Core diameter	1.270 m
Core height	1.0 m

3.3 Accelerator Driven Systems

Accelerator driven systems (ADS) throw open several attractive possibilities for extending our nuclear power programme. High-energy protons, on colliding with a target of high Z element (such as lead, tungsten, uranium etc.) cause detachment of a large number of neutrons from these nuclides in a process known as ‘spallation’. These neutrons can provide the required population to sustain a self-terminating fission chain in an otherwise sub-critical blanket (an arrangement similar to a nuclear reactor with not enough fuel to make it critical). Such a system, called ‘Accelerator Driven System’, can be used to produce several times more electrical energy than that required for operating the accelerator. Such a system is, therefore, also termed as an ‘Energy Amplifier’. The system can also be designed, so as to convert, more efficiently than in a critical reactor, fertile materials, present in the blanket, to fissile materials. Accelerator driven systems are also eminently suited for transmuting the highly radioactive waste from conventional nuclear power plants to shorter lived radio-nuclides, which do not require a very long term storage under surveillance.

India has already made a good start by acquiring the necessary expertise to design and build linear accelerators as well as cyclotrons. The challenges involved in the design of very large accelerators, and coupling them to sub-critical cores, are quite substantial and are matters of intense R&D effort in several countries. As a part of the roadmap for the third stage of Indian Nuclear Power Programme, a set of milestones have been identified, along the way, for the development of the technologies relevant for an accelerator driven system.

As a first step, it is planned to develop high-energy neutron source, which can be used in the Critical Facility, due to be constructed soon at BARC, for physics experiments relating to AHWR and PHWR. This will help in quickly validating relevant neutronic data, which can be used for the design of accelerator driven systems. The next step is to develop a spallation neutron source, utilising molten heavy metal as target, along with a moderate sized accelerator, and use it in a research reactor core for additional R&D on the coupling of this source with a sub-critical core. This experience can then be used to design and develop an accelerator driven fertile to fissile material converter, where the basic objective is to produce fissile material from thorium-232/uranium-238 without generating electricity. The final step will be to build a full-fledged accelerator driven

system, for electricity generation, fissile material production, and nuclear waste incineration applications. Such systems can then work synergistically with the remaining components of the third stage of Indian Nuclear Power Programme.

In order to drive the ADS with a relatively low power accelerator, the concept of using a booster has been proposed. In the neutronic studies carried out at BARC, it has been shown that we can circumvent the high beam current requirement by designing a suitable two-stage energy amplifier. Such a two-stage system consists of a fast sub-critical reactor (booster), which is one way coupled to a thermal reactor. Installing a thermal neutron absorption shield between the two cores as well as keeping the two cores at a distance, so that fission neutrons of thermal core does not interact with the fast booster core, can achieve this. The neutrons from spallation target enter the fast booster core. In this type of an ADS design, it may also be feasible to incorporate a future variant of AHWR design.

There are several key technological areas in which R&D is needed to reach the aforementioned milestones. A detailed plan is being compiled to identify and define the scope of each of these R&D activities.

4. Enabling Technologies

An important feature of the road map is that it provides for progressively building upon already developed technologies to newer technologies in a phased manner. For each of the deliverables indicated in the road map, several enabling technologies are required to be in place. Some of these technologies are given in the following list, which is not exhaustive

4.1 Advanced Heavy Water Reactor

- Natural circulation driven passive core heat removal
- Technologies for stability control in two phase natural circulation flow
- Development of channel power monitoring technique
- Development of passive control valve
- Technologies to avoid thermal stratification in large pools
- Passive containment cooling
- Large passive heat sink
- Moderator heat recovery
- Passive ECCS (Emergency Core Cooling System) of enhanced effectiveness.
- Development of fluidic device
- Easily replaceable coolant channels
- Remotised fuel fabrication technologies
- Pu-Th and Th-U-2333 MOX fuel fabrication technologies.
- Laser isotopic clean-up of U-232.
- Three stream reprocessing of fuel bearing Pu, Th and U.
- Dry reprocessing of fuel
- Nuclear data for nuclides important for the thorium cycle
- Laser isotopic denaturing of Zirconium
- Nuclear desalination

4.2 Compact High Temperature Reactor

- Molten heavy metal coolant technologies
- Advanced TRISO coated fuel particle and related technologies
- Passive reactivity regulation and shutdown devices
- High heat flux, high temperature passive heat removal technologies including heat pipes
- High temperature structural materials resistant to molten heavy metal coolants
- Oxidation and corrosion resistant coating technologies
- Carbon, graphite and carbon-carbon composite technology for manufacturing reactor components

- Reactor physics calculations of compact cores
- Nuclear data for new materials like Bismuth, Gallium
- Sensors for high temperature liquid metal coolant system
- Hydrogen generation technologies
- Technologies for high efficiency electricity generation technologies with static devices and MHD technology

4.3 Accelerator Driven System*

- Development of accelerators in the GeV range and current of the order of milli-amperes
- Development of special materials for spallation source and other structural features
- Accelerator driven spallation source design studies
- Nuclear data relevant for materials and energy spectrum of ADS.
- 14 MeV neutron sources for experimental studies in a sub-critical facility.
- Subcritical Reactor physics with spallation neutrons
- Development of fertile material conversion blankets

5. Conclusion

The technology road map for the third stage of the Indian nuclear programme focuses on achieving a sustainable nuclear energy supply system with (a) optimum utilisation of available nuclear fuel resources, (b) elimination of long-lived nuclear waste, and (c) a capability to meet a variety of future needs of energy and potable water supply. These objectives are applicable to the rest of the world too.

Most of the associated enabling technologies are generic in nature, and will have direct applications in other advanced reactor types and other fuel cycles. This makes these technologies candidates for international co-operative R&D. IAEA's INPRO programme could be a platform for facilitating such co-operative R&D.

Most of these newer technologies are expected to lead to higher performance materials (including radioisotopes), devices and systems that could have important spin-off benefits in non-nuclear fields as well.

6. References

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* This list will be expanded further on the basis of feasibility studies for various systems and subsystems.